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# DEPARTMENT OF DEFENCE

## DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

## AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA



Propulsion Report 182

# THE REDUCTION OF SMOKE EMISSIONS FROM ALLISON T56 ENGINES (U)

by

F.W. Skidmore
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*Royal Australian Air Force



Approved for public release.



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**SUMMARY**

Aeronautical Research Laboratory (ARL) has been working to reduce smoke emissions from the Allison T56 engines used in the Lockheed P-3C Orion aircraft operated by the Royal Australian Air Force (RAAF). The work consisted of a literature survey, design and manufacture of a water tunnel model, water tunnel testing of various modifications to improve the fluid dynamics of the combustion system, testing the modifications in a single liner combustion test rig, smoke emission comparative tests in ground run engine trials, performance tests in a calibrated test cell and flight trials of a modified engine. The modification that was developed in this program was found to significantly reduce smoke emissions and give substantial improvements in the specific fuel consumption of the engine. In addition, there were indications, in line with theoretical predictions, that the modification would extend the life of the hot end components of the engine.

This report describes the work up to August 1989 and outlines the final program on burner outlet surveys that will complete the program.


DSTO ARL MELBOURNE




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## 1. INTRODUCTION

The Royal Australian Air Force (RAAF) uses the P-3C Orion aircraft in a multi-role capacity. One of these roles is in the surveillance and detection of submarines. In this role the smoke emissions from the Allison T56-A-14 engines can be clearly seen by submariners. The submarines, however, remain difficult to detect visually by the aircrew even in a calm sea.

As a result of this problem the Aeronautical Research Laboratory (ARL) was tasked by the RAAF to investigate methods of reducing the smoke emissions from the Allison T56 engines to an acceptable level. The work undertaken by ARL focussed on the combustion system and, in particular, the fluid dynamic aspects which are known to influence the formation of soot. The work program consisted of an initial literature survey, engine exhaust smoke measurements, water tunnel experiments, engine ground tests and, finally, flight trials. The final phase of the program will be a burner outlet temperature survey which has commenced but was not complete at the time of publication.

This work was carried out under Defence Science and Technology (DSTO) Tasks AIR 85/034 and AIR 89/086 and addresses part of the work required by Air Force Research Requirement AFRR 3/88 (1988).

## 2. LITERATURE SURVEY

An extensive literature survey was undertaken and revealed that the main factors influencing smoke emissions from gas turbine combustion systems include;

* the chemical composition of the fuel - in particular the aromatic content and the ratio of hydrogen to carbon,
* the physical design characteristics of the combustor, and
* fuel atomisation and mixing of fuel and air.

## 3. THE ALLISON T56 TURBOPROP ENGINE

The General Motors Detroit Diesel Allison T56 engine is a single spool gas turbine engine driving a propeller through a reduction gear box. This engine is installed in the Lockheed P-3C Orion and C-130 Hercules aircraft operated by the RAAF. The engine has a 14 stage axial flow compressor with a pressure ratio of 9.5 to 1 that delivers air to a can-annular combustion system. Following the combustors the gases pass through a 4 stage axial flow turbine.

The engine is designed to operate at a constant speed of 13,820 RPM which is controlled by using a variable pitch propeller. This implies that, at any given altitude and speed, airflow and pressure through the engine are constant.
The combustion system has undergone only minor design changes since the engine was brought into service in the early 1960's. Figure 1 shows a diagrammatic layout of the system which consists of:

* inner and outer pressure casings that provide both the gas path connection between the compressor and turbine and the mechanical connection;

* six individual combustor liners that control the airflow distribution and airflow pattern required for stable combustion; and

* six dual orifice atomisers.

The RAAF operates three variants of the T56 engine as shown in Table 1.

**TABLE 1.**

**T56 ENGINES OPERATED BY THE RAAF**

| ENGINE TYPE | SERIES | AIRCRAFT |
|---|---|---|
| T56-A-7B | II | Hercules C-130E |
| T56-A-15 | III | Hercules C-130H |
| T56-A-14 | III | Orion P-3C |

All three versions emit visible smoke, but (subjectively) the Series III engine was considered to emit more smoke than the Series II engines. This contention was established as part of the present study. Souza and Daley (1978) showed that the Series II engines have an average SAE smoke number of 45 at maximum power, and Skidmore (1985), as part of the present study, measured the Series III, T56-A-14, engine exhaust smoke number as an average of 50.9 for the same power setting. Using the information contained in Champagne (1971) this can be shown to represent a 50% increase in the mass emissions of smoke particles at that power setting. Further analysis of the information contained in Souza and Daley (1978), Vaught et al. (1971) and Skidmore (1985) on the smoke emissions from the two series of engines shows that the Series II engine emits less smoke than the Series III over the entire power range.

The combustion systems of the two Series III engines are identical. However, there are certain differences between the Series II and Series III systems. Figure 2 shows a photograph of the two types of combustor liner. The larger outlet section of the Series III is necessary to accommodate a different turbine and there are variation in air hole geometry between the liners.

By using the work of Knight and Walters (1953) and Adkins and Gueroui (1986) in determining discharge coefficients of air holes and cooling corrugations in combustor liners, Skidmore (1986), as part of the present study, estimated the distribution of airflows for the two liners. These distributions are given in Figure 3. and show that the total primary zone airflow is estimated to have been increased from 14.3% to 15.3% of the total flow from the Series II to the Series III configuration. This involved an increase in the dome airflow from 5.4% to 8.1% and decrease in the airflow of the first primary zone holes from 6.4% to 3.4% of total airflow.

## 4. INITIAL ENGINE TESTS

### 4.1 Scope of Tests

Smoke emission tests were carried out at the RAAF Bases in Edinburgh, South Australia and Richmond, New South Wales on the three variants of T56 engine operated by the RAAF. Table 4.1. lists the types, series and serial numbers of the subject engines. All engines were tested for smoke emissions using the equipment and procedure described in the SAE's ARP 1179A (1980) over the full operating range from low speed ground idle to full power. Figure 4. shows an Allison T56-A-14 engine mounted on a mobile engine test stand at Edinburgh RAAF base during one of the smoke emission tests. Figure 5. shows the engine from the rear with the gas sampling probe in position.

**TABLE 4.1**

**T56 ENGINES TESTED**

| ENGINE TYPE | SERIES | SERIAL NUMBER |
|---|---|---|
| T56-A-14 | III | AE 110294 |
| T56-A-14 | III | AE 107029 |
| T56-A-15 | III | AE 108518 |
| T56-A-15 | III | AE110432 |
| T56-A-15 | III | AE106208 |
| T56-A-7B | II | AE 105574 |
| T56-A-7B | II | AE 106173 |
| T56-A-7B | II | AE 105593 |

### 4.2 Results and Discussion

The results of these tests are fully presented in Skidmore (1985 and 1986). Summary data are presented in Figure 6 in terms of SAE Smoke Number against Engine Power. The results agree well with other published data on smoke emissions from Allison T56 engines (Souza and Daley, 1978 and Vaught et al, 1971). They confirm that the engines all emit smoke at a level which is both above the US EPA (1973) limit for smoke emissions for the T56 engine fitted to the C-130 Hercules aircraft (Matterson et al, 1980).

## 5. WATER TUNNEL EXPERIMENTS

A water tunnel model representing part of the T56 combustion system was designed and built at ARL and tested at the Swinburne Institute of Technology. The model, shown in Figure 7, was based on a carefully designed 60 degree sector of the annular pressure casing of the combustion system. The two plane radial sides and the curved walls representing the inner and outer casing segments were made from Perspex. The metal combustor liner was fitted with cutouts to permit Mylar windows to be inserted to allow the internal flow field to be observed when dye was injected at various stations along the model. The tests carried out with the model were conducted at Reynolds numbers that ensured that the large scale flow field of the engine was reproduced.

The flow field within the standard combustor was found to be deficient in several respects, and various modifications were developed to radically improve the turbulent mixing within the combustor. The development of the final modification was the result of an extensive series of tests in which a wide range of possibilities were considered.

## 6. COMBUSTION RIG TESTS

### 6.1. Apparatus and Test Procedure

The modifications that were developed in the water tunnel were tested in a combustion test rig at ARL for comparison with the performance of a standard combustion system.

A photograph of the rig is shown in Figure 8 and a cross sectional view appears in Figure 9 Like the water tunnel model, the rig was based on a single liner contained in a 60 degree sector of the Allison T56 combustion system. The sector, shown in Figure 10, had insulated radial side panels to reduce circumferential heat loss, and both the inner and outer pressure casings of the engine were reproduced in 0.5 mm stainless steel. There were two sectors available for the rig; the one, shown in Figure 10, accepted Series II combustor liners while the other accepted Series III liners. The sectors were used only to act as guides for airflow through the rig and the pressure was contained by a 300 mm mild steel casing. The inlet diffuser, shown in Figure 11, was an exact copy of the actual engine diffuser.

The validity of the combustion rig in representation of part of the full scale engine combustion system, could be assessed in two ways. These were in terms of gaseous and particulate emissions which were similar to published data, and in terms of the distribution of metal temperature on the surface of the combustor liner. Figure 12 shows the temperature distribution patterns revealed by thermal paint on the surface of a standard liner after operation in the rig together with the natural metal temperature discolourations on the same liner after operation in an engine. These patterns can be seen to be essentially the same, with even small features of the pattern accurately reproduced.

The rig could operate at pressures up to 1000 kPa (150 psi) and with inlet air temperatures up to $350^{o}C$ ($660^{o}F$).

The conditions chosen for these tests were:

- air mass flow - 2.15 kg/s (4.75 lb/s);
- rig inlet pressure - 760 kPa (110 psi); and
- rig inlet temperature - 300°C (570°F).

This corresponds to an operating condition for the T56 engine at a low level cruise in the P-3 Orion. While it was possible to have rig outlet (or turbine inlet temperatures) up to 1100°C, for this series of tests the outlet temperature was limited to 900°C, corresponding to a power setting just below the normal cruise setting for the engine.

Smoke emissions were determined using the same equipment used in the engine tests (see Section 4). Gaseous emissions were determined using the equipment and procedure described in the SAE's ARP 1256A (1980).

### 6.2 Results and Discussion

The effectiveness of a modification was assessed in terms of SAE Smoke Number, gravimetric carbon emissions (smoke), emissions of unburnt hydrocarbons, carbon monoxide and oxides of nitrogen. The modification developed in the water tunnel work was tested and subsequently modified in minor ways to achieve the final modification. The results for the final modification developed at ARL are shown plotted against turbine inlet temperature in Figures 13 to 17 Figure 14 was obtained by converting the SAE Smoke Number to emissions of carbon using the information contained in Champagne (1971).

These results, with the exception of oxides of nitrogen, all show a reduction in emissions. (The levels of unburnt hydrocarbons at higher turbine inlet temperatures were very low for both the standard and modified liners and probably reflect the background levels of hydrocarbons or oil in the inlet air to the rig rather than an effect due to the modification). The slight increase in oxides of nitrogen indicate a higher flame temperature or an increase in residence time in the combustor which is consistent with more stable and efficient combustion in the modified combustor. All of the results show that combustion in the modified combustor liner had been improved. In particular smoke emissions had been reduced significantly, and the overall results pointed to an increase in combustion efficiency.

## 7. MODIFIED ENGINE GROUND TESTS

### 7.1 Scope of Tests

The performance of the modified combustion system was compared with the performance of a standard system in a series of ground run engine trials addressing three aspects.

These were:

- exhaust smoke emissions (measured on an open test stand);
- engine performance and specific fuel consumption (measured in a calibrated test cell); and
- durability of the combustor liner, nozzle guide vanes and turbine blades.

### 7.2 Open Test Stand Trials

The open test stand trials were conducted on an Allison T56-A-14 engine (S/N AE 110298) at the RAAF Base in Edinburgh, South Australia. The engine was initially tested in standard form for smoke emissions over the entire power range from low speed ground idle (start position) to maximum power, to establish a valid base-line measurement. This test involved about four hours of engine running. The engine was then dismantled and modified to incorporate the ARL low smoke combustor liners that contained the final geometry established in the ARL laboratory rig tests. Care was then taken to ensure that the engine was rebuilt with all components in exactly the same position; **i.e. the only difference was the ARL low smoke modification to the combustor liners.** The engine was then retested at the same conditions that were used previously in testing the standard engine. A fuel sample was collected at the conclusion of each trial and analysed by the Australian Department of Defence, Materials Testing Laboratory in New South Wales for physical and chemical characteristics (including hydrogen and aromatic contents). These analyses are reproduced in Appendix 1. At the conclusion of the smoke reduction trials a durability test commenced.

### 7.3 Results and Discussion - Open Test Stand

The results of the smoke emission tests from the ground run engine for both the standard and modified engine builds are shown in Figure 18 in terms of SAE Smoke Number versus engine power and in Figure 19 for mass emissions of carbon (smoke) versus engine power. Figure 20 shows the percentage reduction in mass emissions of carbon attributable to the combustor modification together with corresponding data from the combustion rig.

These results show that smoke emissions were reduced by a substantial margin over the entire operating range of the engine. The percentage reduction is also in close agreement with the reduction observed in the laboratory rig tests (Figure 20).

The results of the fuel analysis (Appendix 1) show that the difference in both aromatic and hydrogen content is very small and would have had a negligible effect on smoke emission differences.

The level of smoke emissions from the modified engine approaches the visibility threshold level for a C-130 Hercules aircraft, see Matterson et al (1980). No information regarding the visibility threshold level could be found for the P-3 Orion aircraft. However, a comparison of the two engine installations suggests that the P-3 would be more likely to generate discrete visible smoke trails than would the C-130 aircraft.

The smell of unburnt fuel is usually noticeable in the exhaust of standard T56 engines, particularly at low power settings. During the ground trials there was no smell * of unburnt fuel in the exhaust of the modified engine at any power setting. This was consistent with the rig results for unburnt hydrocarbon emissions.

Another positive aspect which was noticed during ground running was that the modified engine was easier to start and emitted no smoke during the starting cycle. Peak start-up temperatures were also lower.

### 7.4 Durability Test

The same modified engine was subjected to an extended run designed to test the durability of the modified liners and to ensure that the modification did not reduce the life of the nozzle guide vanes or turbine blades. The test consisted of running the engine for 10 minutes at ground idle (start position) followed immediately by 10 minutes at maximum continuous power (1010$^{o}$C turbine inlet temperature). Both increases and decreases in power were carried out as rapidly as possible. This cycle was repeated for approximately 12 hours per day until 150 hours of engine running time had been accumulated. This testing program was considered to be the equivalent of at least 1000 hours of normal flight operation by the RAAF. During the run, regular boroscope examinations were undertaken of the liners, nozzle guide vanes and first stage turbine blades. Subsequently the engine was dismantled and inspected by experienced RAAF Engine Fitters. Inspection revealed that there was no sign of any distress or any other problem in hot end components. In fact the hot end components appeared to be in significantly better condition than those of a standard engine; this was particularly so for the liners. The modified liners after the 150 hour endurance test were completely free from any cracks or any other sign of distress, whereas the (new) standard liners that had been run for only about four hours all contained cracks in the area near the exhaust. It was most noticeable that the modified combustor liners were virtually free from carbon build-up and this contrasted with the standard liners which were coated in carbon. Figure 21 shows comparative boroscope photographs of the area around the dome of the liner for both a standard and modified liner.

It is anticipated that the significant reduction in carbon generation will increase the life of turbine blades and nozzle guide vanes. This is based on evidence that the protective coatings on these components are eroded by carbon particles which decreases the life of the coatings, and thus the life of the blade. Current testing will, in time, provide data on this aspect of the modification.

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The smell of unburnt hydrocarbons can be an operational problem for the C-130 when taxiing for extended periods with troops on board, with the rear ramp deployed for ventilation.

### 7.5 Performance Tests

The modified engine was installed in the calibrated T56 test cell at QANTAS in Sydney, and subjected to a series of performance measurements. The engine was then returned to standard configuration and retested for performance. Subsequently another T56-A-14 and a T56-A-15 engine were tested with modified liners in the calibrated test cell to expand the data base on engine performance with the modified liners.

The results in terms of the percentage improvement in corrected specific fuel consumption versus turbine inlet temperature are presented in Figure 22 for the three modified engines. Figure 23 provides the same information but as an average of the results for the three engines. The results demonstrate that, for the engines tested, specific fuel consumption was reduced by approximately 1% at the normal cruise condition for the engine.

These results will be confirmed by testing further modified engines.

## 8. FLIGHT TRIALS

### 8.1 Scope of Flight Tests

At the conclusion of the calibrated test cell runs, the first engine (S/N AE 110298) was again rebuilt to the low smoke configuration and fitted to number 3 position on the RAAF's P-3C Orion aircraft, A9-661. Engine performance and behaviour were monitored in flight using standard aircraft instrumentation that had been calibrated. A video camera mounted behind the co-pilot was used to record the engine instrumentation parameters. A second hand-held video camera was also used on some tests to record instrument and general flight information. The flight trials were conducted under RAAF Special Technical Instruction TI 1045 (1989) during June 1989.

The trials were conducted in two phases. The first phase was based on the standard flight test following an engine change as required by the P-3C Flight Manual (RAAF, 1983) and included safety checks of the relight capabilities of the engine. The second phase was designed to test the modified engine throughout the flight envelope of the P-3C aircraft to ensure that relight or flameout characteristics of the engine were not compromised.

A chase aircraft was used to record, photographically, variations in smoke emissions from the engines in flight. Photographic and video recordings were also taken from the ground during take-offs and landings and also during a series of fly-overs.

The program for the second series of tests was:

a. Tests to identify any changes in the relight characteristics of the modified engine.
   This was achieved by flying the aircraft at an indicated airspeed of 170 Kts and shutting down an unmodified engine for 30 minutes to allow the engine to be cold soaked. The engine was then restarted and the following recorded: (1) time to start, (2) maximum peak turbine inlet temperature reached during start up, and (3) the time for the temperature to stabilise following ignition. This procedure was then repeated with the modified engine. The test was conducted at altitudes of 30,000, 20,000, 10,000 and 500 feet.

b. A test requiring the aircraft to be flown at maximum speed at altitudes of 30,000, 20,000, 10,000 and 500 feet and reducing power on engines number 2 and 3 (standard and modified) as rapidly as possible to check for possible lean extinction.

c. Tests including aircraft stalls, negative and positive accelerations, full reverse power operation, and general rough handling.

d. A ground test requiring the aircraft to pass through the aircraft washing facility ("bird bath") with all engines operating.

### 8.2 Results and Discussion

Observations from the ground and from the chase aircraft confirmed a significant smoke reduction. Photographic recordings (Figure 24) show a very faint smoke emission from the modified engine but this is minimal compared with the large trails that can be seen from the three standard engines. The poor definition in the photograph is due to the heavy rain that persisted throughout the tests.

These tests showed that:

a. for all tests the modified engine performed within the allowable limits in the flight manual specifications and;

b. the modified engine showed no tendency to flame out during extreme in-flight manoeuvres and operation in the aircraft washing facility.

At the conclusion of the flight tests the RAAF accepted the modified engine for normal squadron operation without restrictions or further testing apart from routine maintenance. At the time of writing this report the engine had completed 250 hours on-wing. Boroscope examination showed that carbon build-up within the combustor was still very light compared to standard systems.

## 9. FUTURE WORK

### 9.1 Flight Trials

The current aim is to have a RAAF P-3C Orion fitted with four modified engines within the next 12 months. Trials with additional engines will proceed as engines become available for overhaul. The next modified engine flight trials are scheduled to commence in October 1989 when a P-3C will be fitted with two modified engines. These trials will be similar to the single engine trials. The modification will also be tested for performance on a Series II, (T56-A-7B) engine before the end of 1989. Complete fleet conversion will occur over a period of several years as engines become available following normal scheduled overhaul.

### 9.2 Burner Outlet Temperature Surveys

There are quantitative data indicating that the ARL modification has improved the temperature distribution at the burner outlet and decreased the metal temperature of the liner. Additional tests to gather further data to support this conclusion have commenced. The test program comprises:

a. A series of tests to determine the combustor outlet temperature pattern factor for both a standard and modified combustor in the ARL test rig. This will be carried out using a thermocouple rake that will traverse the outlet of the combustor in small increments at various operating conditions allowing 300 individual temperature data points. The conditions will include take-off, maximum continuous power and normal cruise.

b. Liner surface temperature surveys using attached thermocouples and temperature sensitive paints for both the standard and modified liners, to determine changes in metal temperature caused by the liner modification,

c. A series of tests to accurately determine the relight and flame-out characteristics for both the standard and modified liner, and,

d. A series of trials to determine burner outlet temperature profiles on a ground run engine with both standard and modified liners.

## 10 CONCLUSIONS

It has been demonstrated that the ARL developed low smoke modification for the Allison T56 Series III engine reduces smoke emissions from the engine by 80% at low altitude cruise power settings and about 70% at high power settings. The modification at the same time reduces the specific fuel consumption by about 1% at the cruise condition. Flight and endurance trials have not revealed any impairment of behaviour or durability of the modified engine; on the contrary, the modification appears to have increased the durability of the hot end components. The present evidence for this is the absence of liner cracking and a marked reduction in carbon build-up. On-wing durability testing now in progress will provide further data on this conclusion. The engine is easier to start, has lower peak start up temperatures and emits no smoke during start up. The engine is also less smelly due to the reduction of unburnt hydrocarbon emissions. There has been no penalty to be traded for these benefits.

The modified engine has now been released for service on the RAAF's P-3C Orion aircraft A9-661 without any restrictions or further testing and, at the time of publication, the aircraft was operating in normal squadron service. During 250 hours of normal squadron operation, boroscope examination has revealed no cracking and only a very light build-up of carbon confined to small areas, unlike the standard combustor which tends to have large areas covered in carbon with some areas of heavy carbon build-up.

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# APPENDIX 1

# ANALYSIS OF FUEL SAMPLES

**SAMPLE S89/545 WAS USED ON THE STANDARD ENGINE**
**SAMPLE S89/546 WAS USED ON THE MODIFIED ENGINE**

MATERIALS TESTING LABORATORIES - NSW

Schedule A to:
Laboratory Report 89/201
Samples Nos. 89/545 to 552
File FL/REP/DEF

EXAMINATION OF AVIATION FUEL

RESULTS OF EXAMINATION:

| TEST | | METHOD (IP/ASTM) | SPECIFICATION | RESULTS | | | |
|---|---|---|---|---|---|---|---|
| | | | | S89/545 | S89/546 | S89/547 | S89/548 |
| Appearance | | Visual | Clear, bright and free from sediment, suspended matter and undissolved water. | Trace of sediment present. | Conforms | Trace of sediment present. | Trace of sediment present. |
| Colour (Lovibond) | IP Units | 178/- | 4 Maximum | (1.0)-1.25 | (0.75)-1.0 | (0.75)-1.0 | (0.75)-1.0 |
| Distillation | | 123/D86 | | | | | |
| Initial Boiling Point | °C | | Report | 150.0 | 146.5 | 149.0 | 148.5 |
| 20% Vol Recovered at | °C | | 200 Maximum | 170.5 | 170.0 | 173.0 | 172.0 |
| 50% Vol Recovered at | °C | | Report | 187.5 | 187.0 | 190.0 | 188.5 |
| 90% Vol Recovered at | °C | | Report | 221.0 | 222.5 | 225.0 | 223.0 |
| Final Boiling Point | °C | | 300 Maximum | 259.0 | 250.5 | 253.5 | 250.5 |
| Residue | % vol | | 1.5 Maximum | 1.5 | 1.5 | 1.5 | 1.0 |
| Loss | % vol | | 1.5 Maximum | 1.5 | 1.0 | 1.0 | 1.0 |
| Density at 15 °C | kg/L | 365/D4052 | 0.775 to 0.830 | 0.7894 | 0.7912 | 0.7909 | 0.7906 |
| Flash Point (Abel) | °C | 170/- | 38 Minimum | 43.5 | 42.5 | 41.5 | 41.0 |
| Copper Corrosion (Bomb, 2h at 100°C) | | 154/D130 | | | | | |
| | Classification | | 1 Maximum | 1a | 1a | 1a | 1a |
| Existent Gum | mg/100 mL | 131/D381 | 7 Maximum | 8 | 1 | 5 | <1 |
| Water Reaction | | 289/D1094 | | | | | |
| Interface Rating | | | 1b Maximum | 1b | 1b | 1b | 1b |
| Separation Rating | | | 2 Maximum | 2 | 2 | 2 | 2 |
| Aromatics | % vol | 156/D1319 | 22 Maximum | 15.0 | 16.8 | 16.1 | 15.7 |
| Olefin Content | % vol | 156/D1319 | 5 Maximum | 1.3 | 0.8 | 1.2 | 1.2 |
| Hydrogen Content | % mass | 338/D3701 | To be reported | 14.09 | 14.06 | 14.04 | 14.04 |
| Smoke Point | mm | 57/- | 20 Minimum | 27 | 27 | 26 | 26 |
| Aniline Point | °C | 2/611 | To be reported | 61.70 | 60.70 | 61.10 | 61.40 |
| Gravity °API | | 160/D1298 | To be reported | 47.7 | 47.3 | 47.3 | 47.4 |
| Aniline Gravity Product | | 2 & 57/ D611 & 1298 | 4 800 Minimum | 6 824 | 6 682 | 6 716 | 6 755 |

The latest edition of the test methods was used unless otherwise stated.

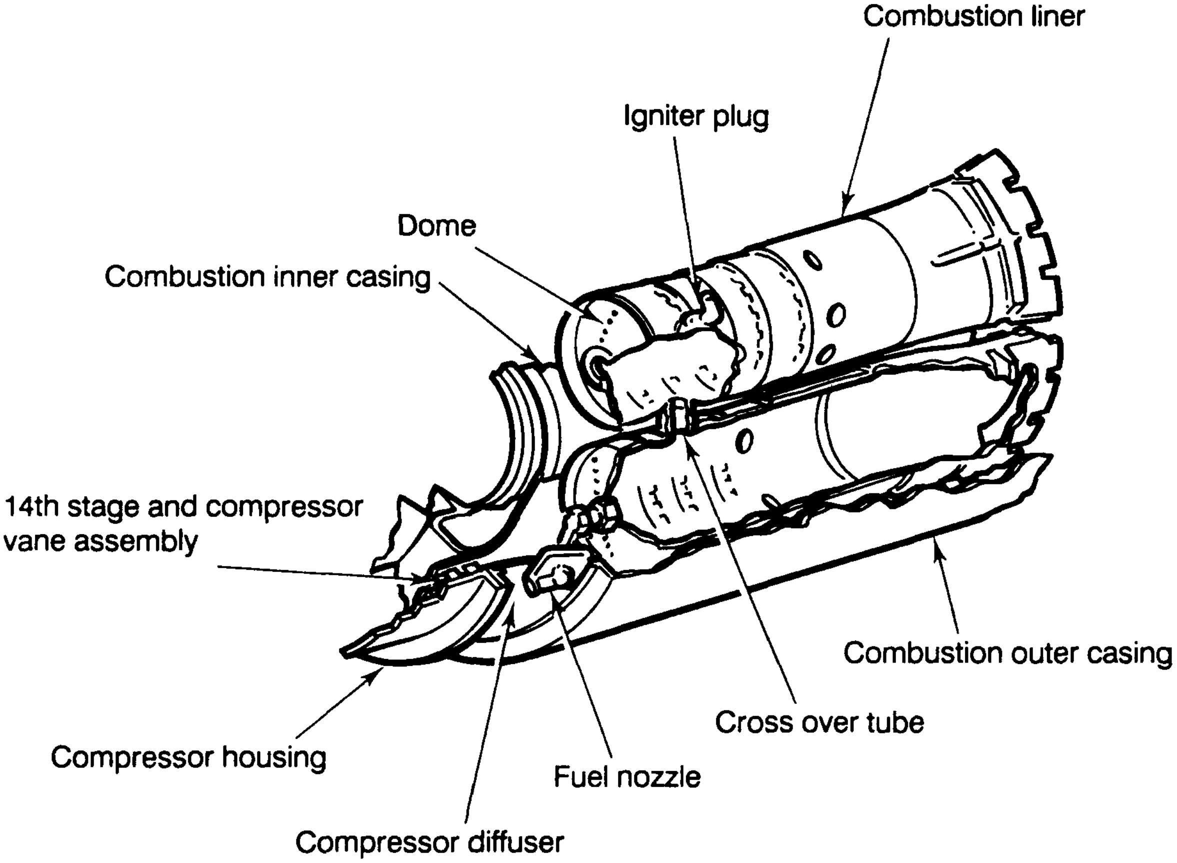
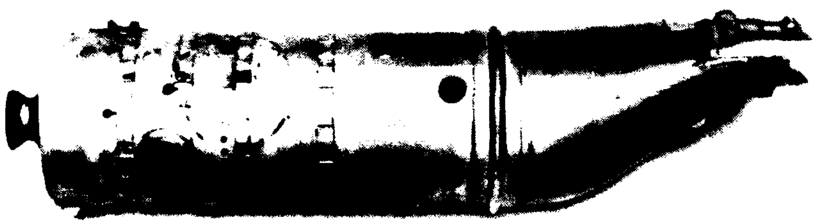


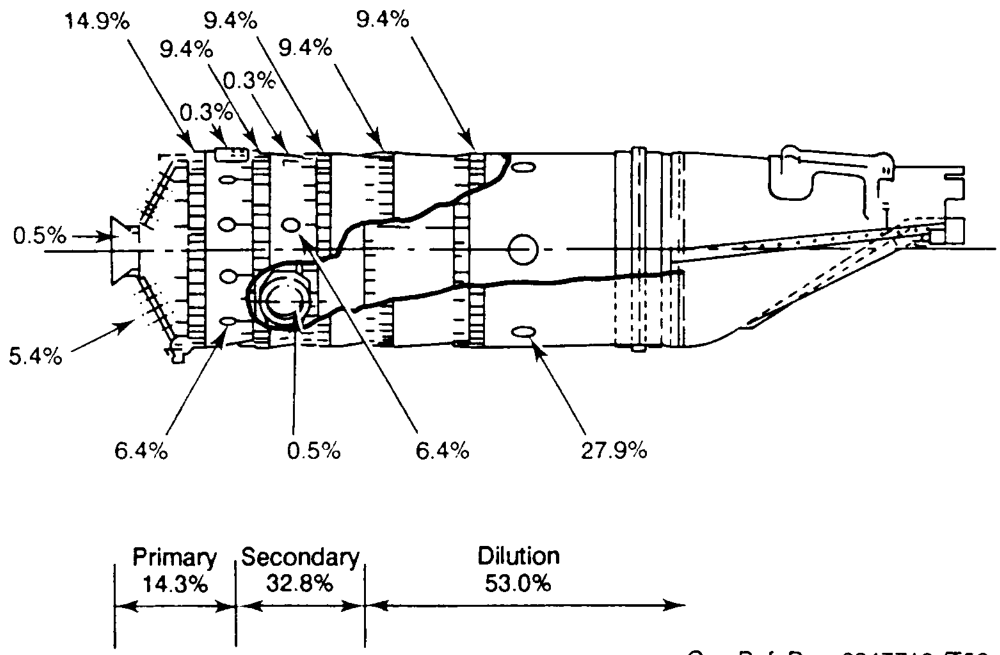

FIG. 1 ALLISON T56 COMBUSTION CHAMBER DETAILS

ALLISON T56 SERIES II COMBUSTOR LINER



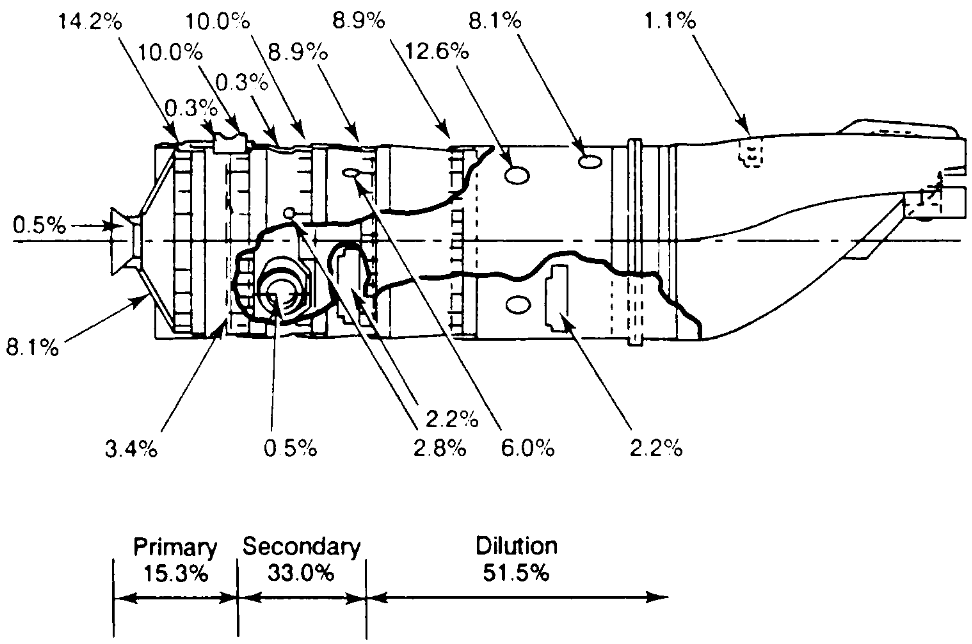
ALLISON T56 SERIES III COMBUSTOR LINER

FIG. 2 ALLISON T56 COMBUSTOR LINERS




Can Ref. Drg 6847712 (T56-A-7)

AIRFLOW DISTRIBUTION OF T56 SERIES II COMBUSTION LINER

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AIRFLOW DISTRIBUTION OF T56 SERIES III COMBUSTOR LINER

FIG. 3 AIRFLOW DISTRIBUTION OF ALLISON COMBUSTOR LINERS

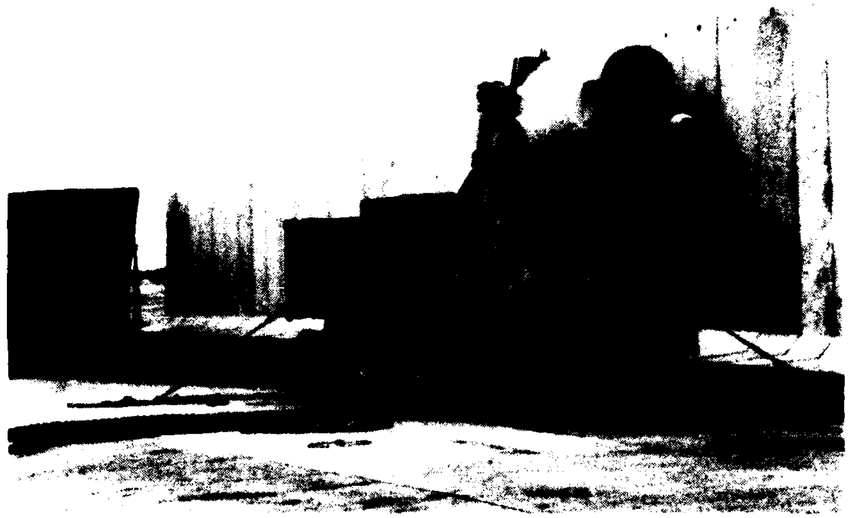


FIG. 4 T56-A-14 ENGINE MOUNTED ON A MOBILE ENGINE TEST STAND

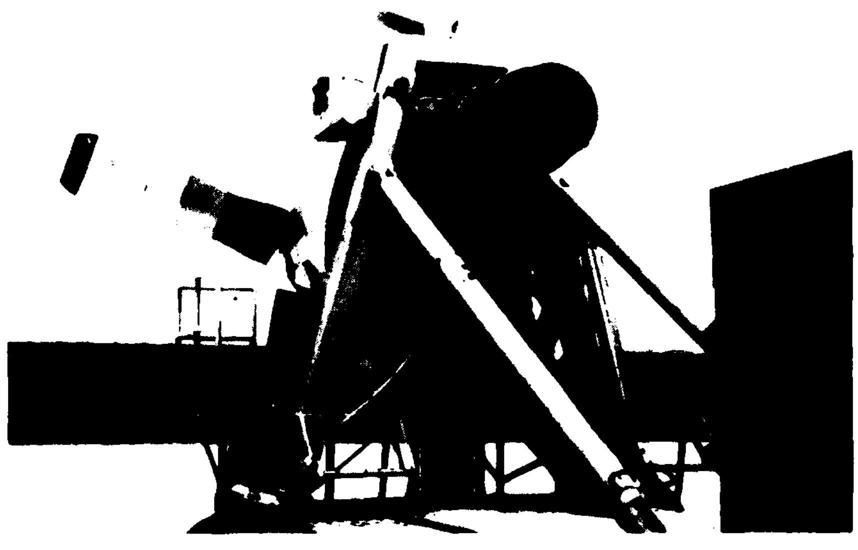


FIG. 5 SMOKE SAMPLING PROBE MOUNTED ON T56-A-14 EXHAUST NOZZLE

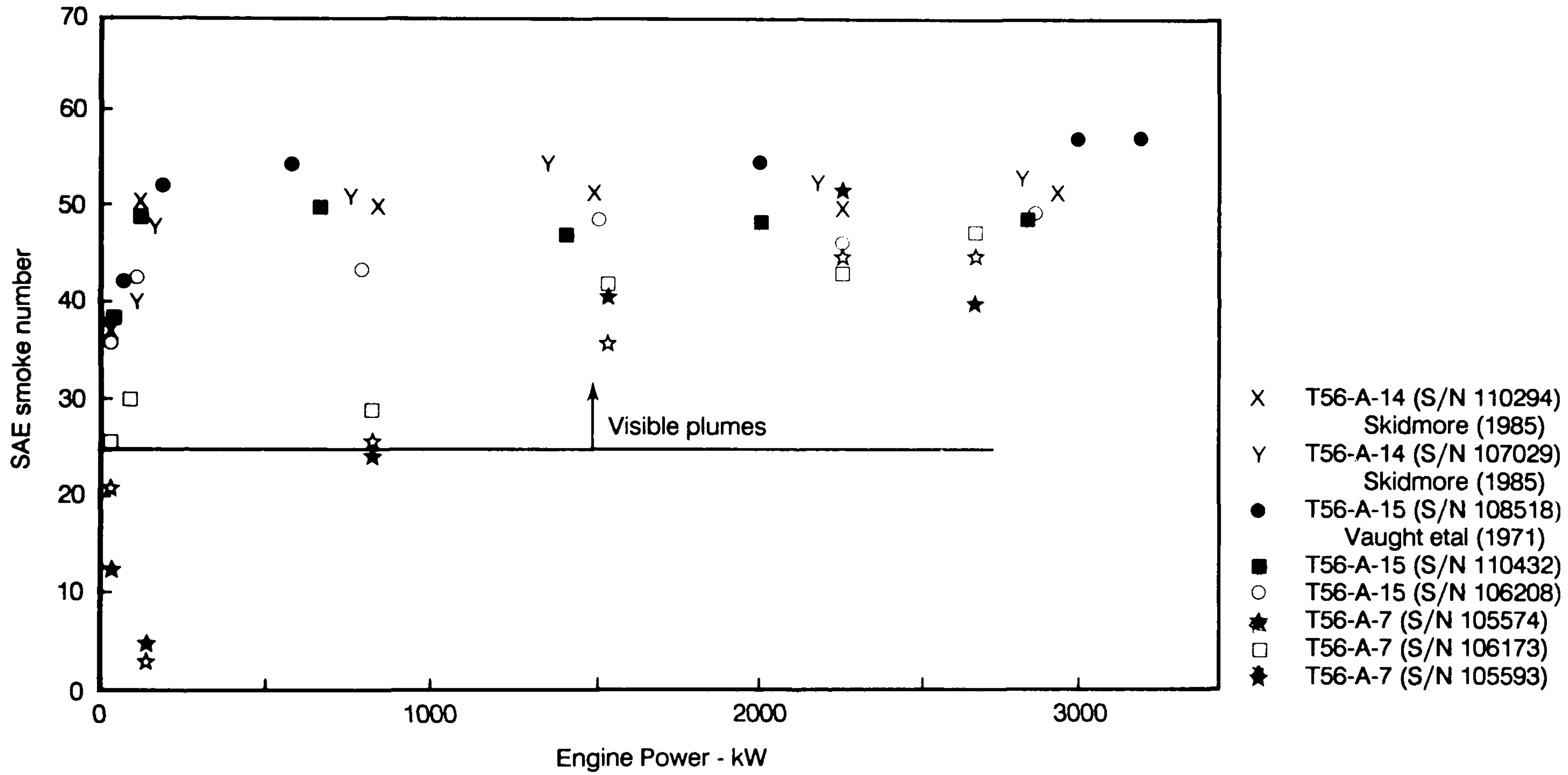



FIG. 6 SMOKE NUMBER VERSUS POWER - T56 ENGINES

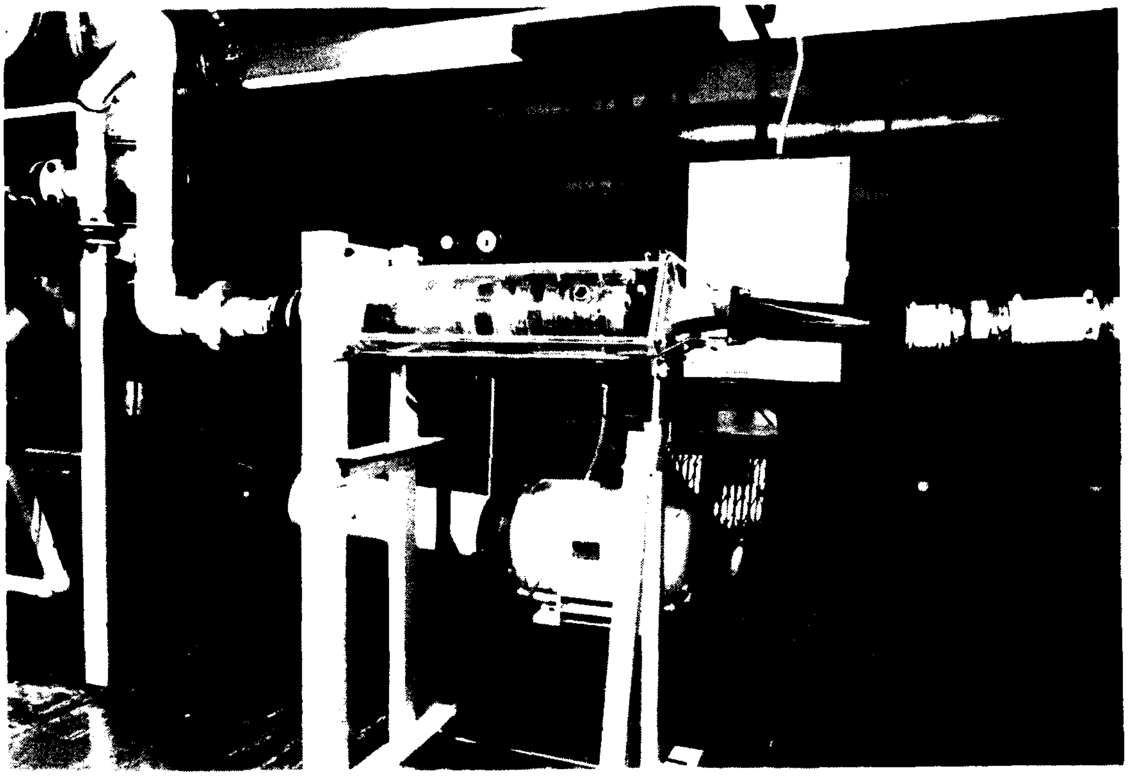


FIG. 7 T56 WATER TUNNEL

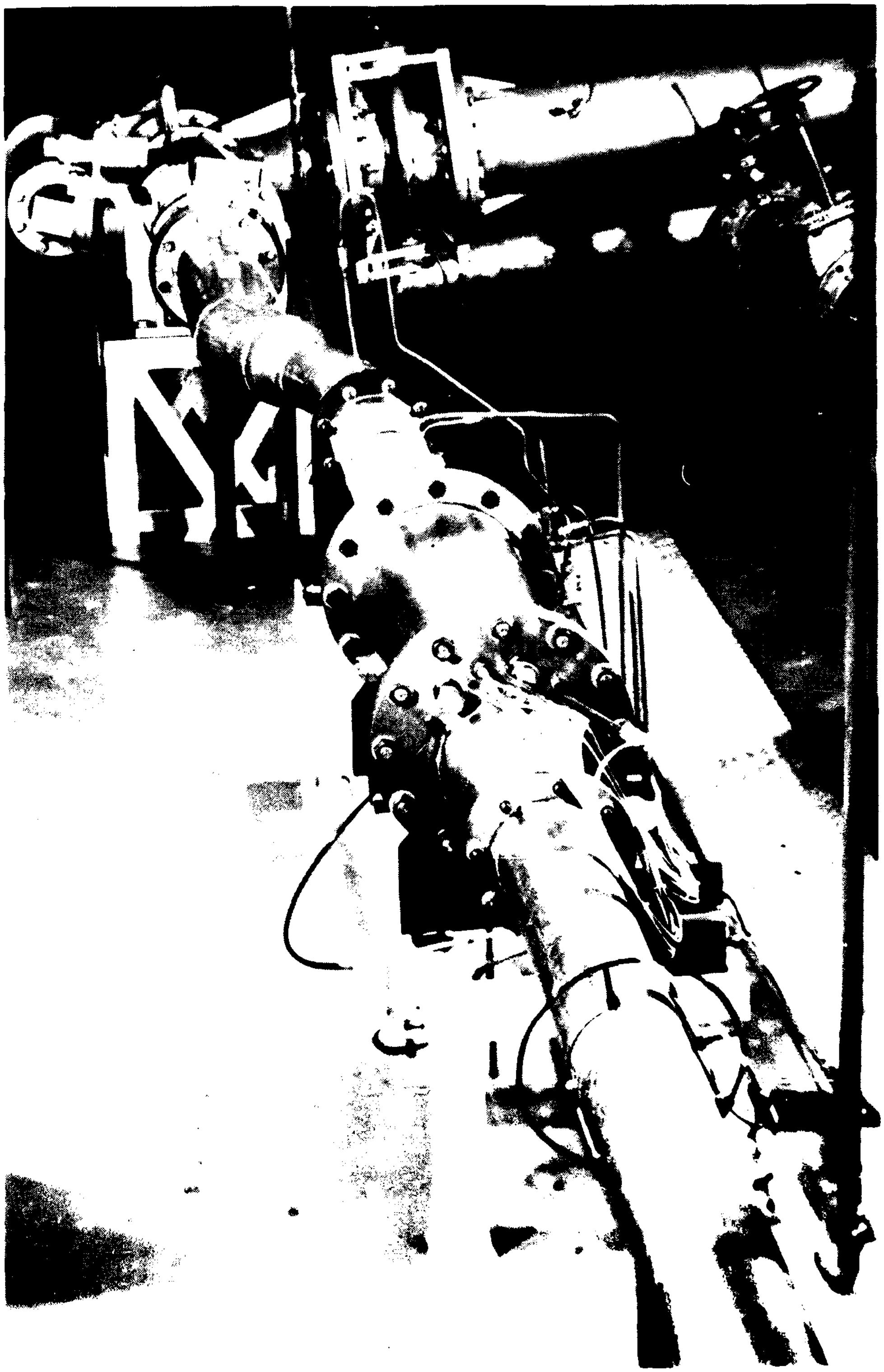


FIG. 8 T56 COMBUSTION TEST RIG

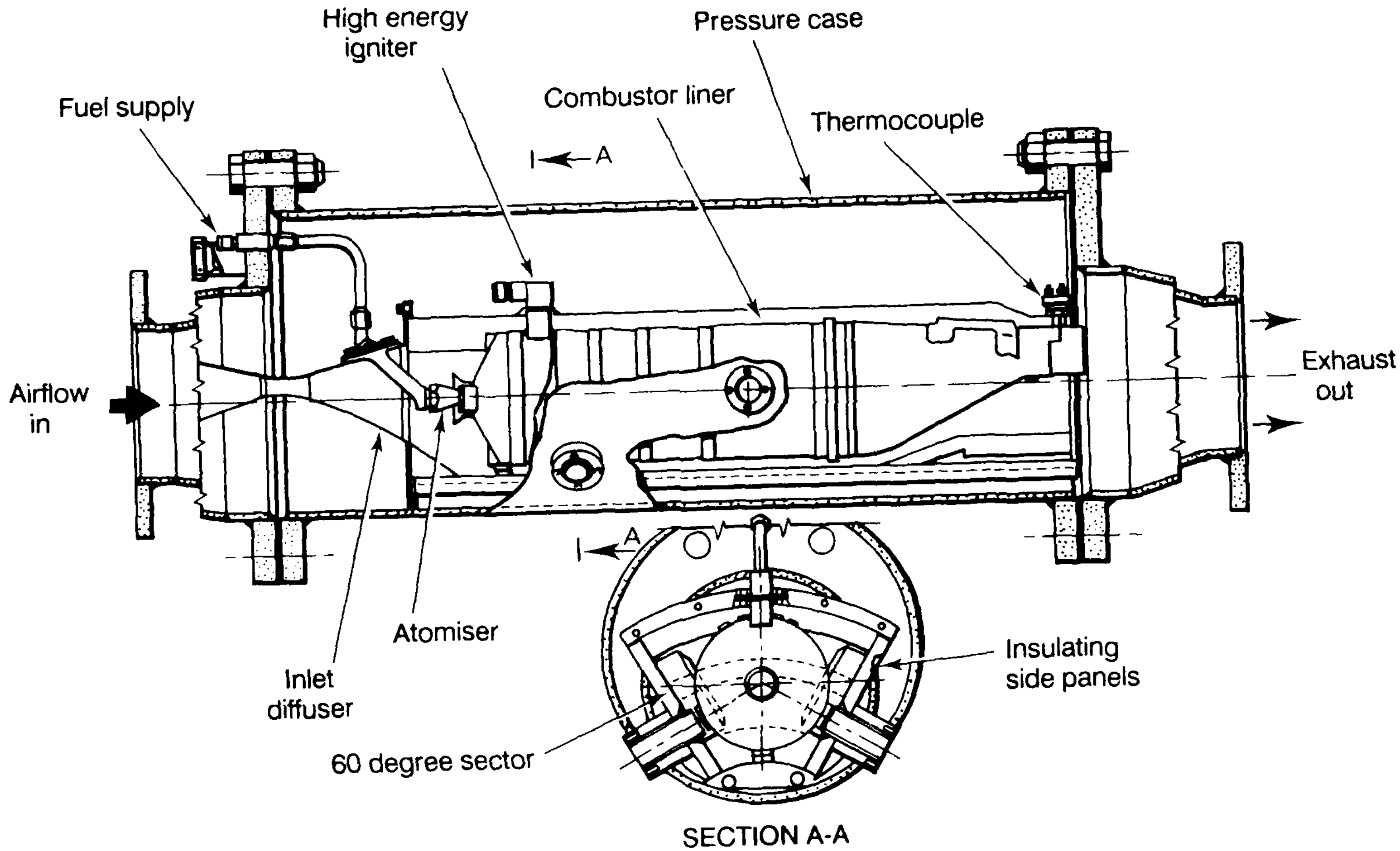



FIG. 9 SCHEMATIC OF T56 COMBUSTION TEST RIG

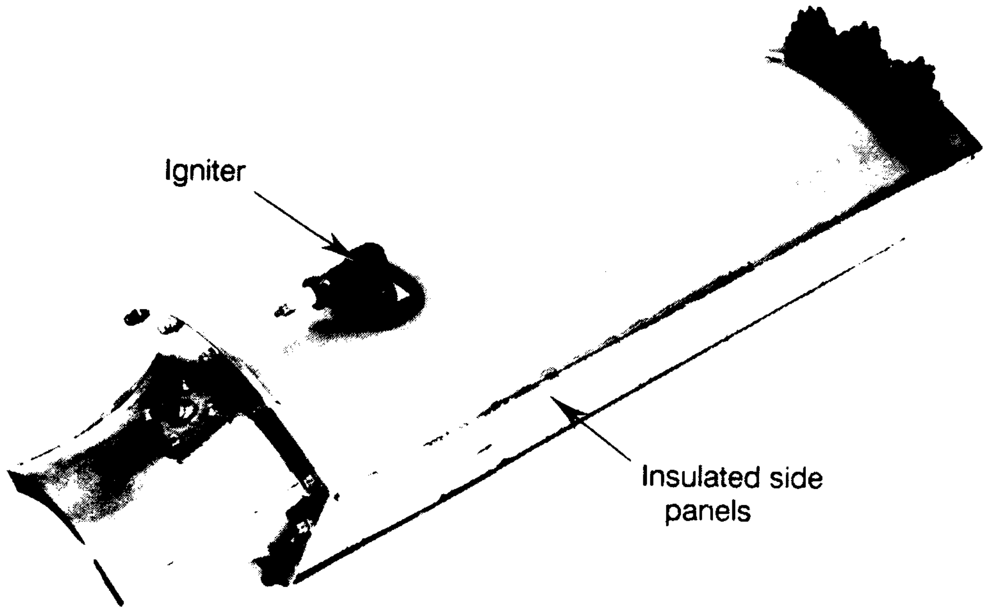



FIG. 10 T56 60 DEGREE SECTOR

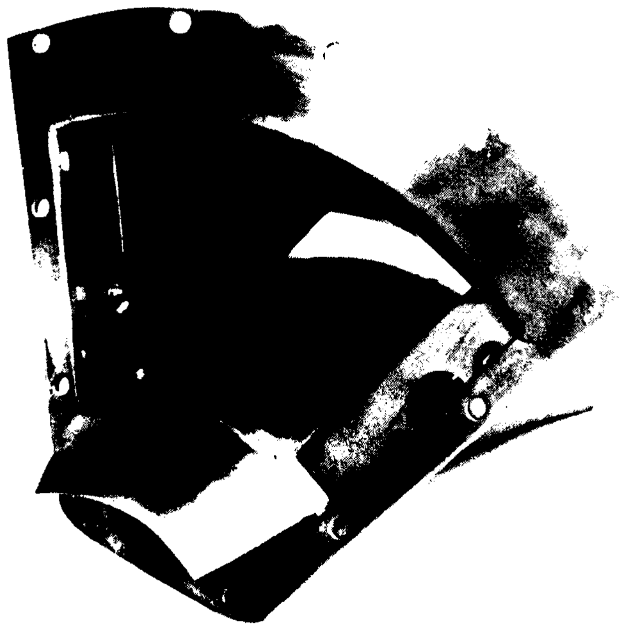
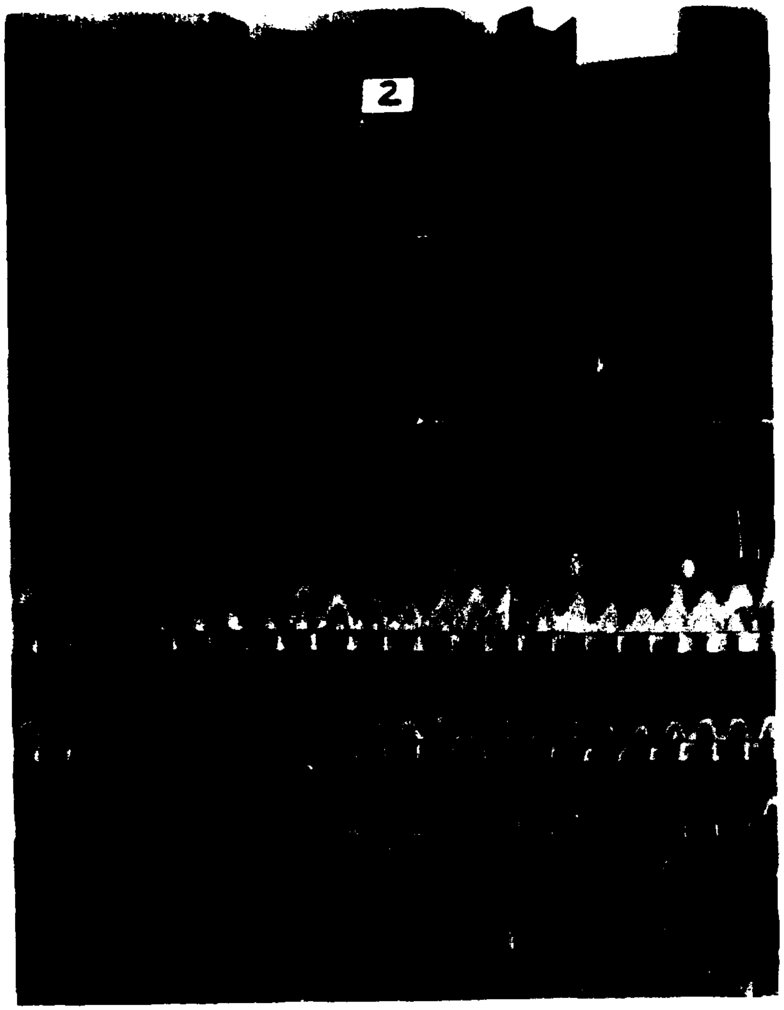
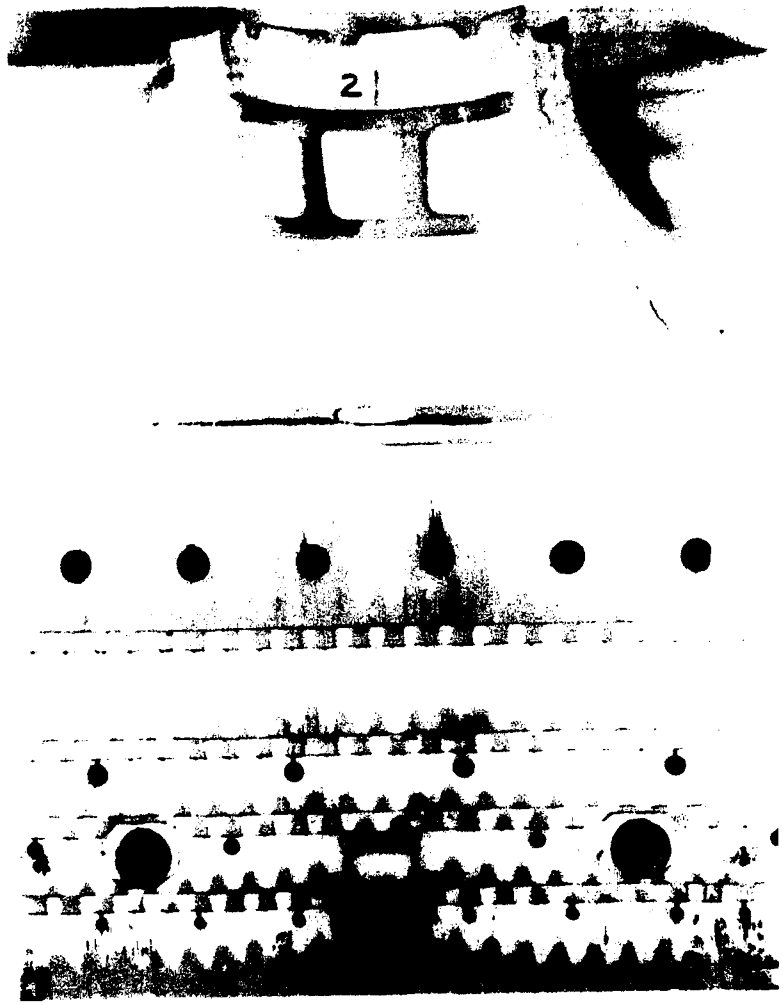


FIG. 11 T56 RIG INLET DIFFUSER




T56 FLAME TUBE
natural heat discolouration




SAME FLAME TUBE
with temperature indicating paint

FIG. 12 PERIPHERAL CAMERA RESULTS

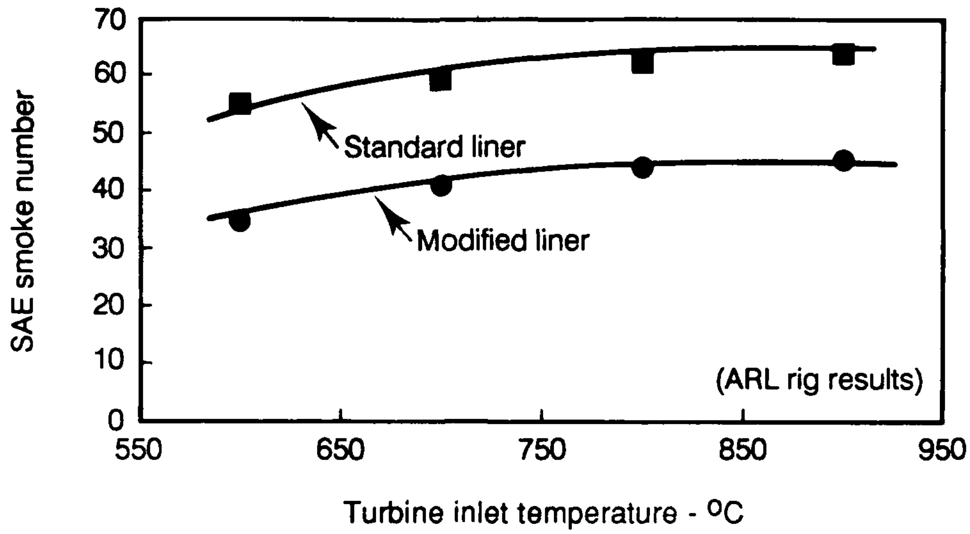



FIG. 13 SAE SMOKE NUMBER VS TURBINE INLET TEMPERATURE

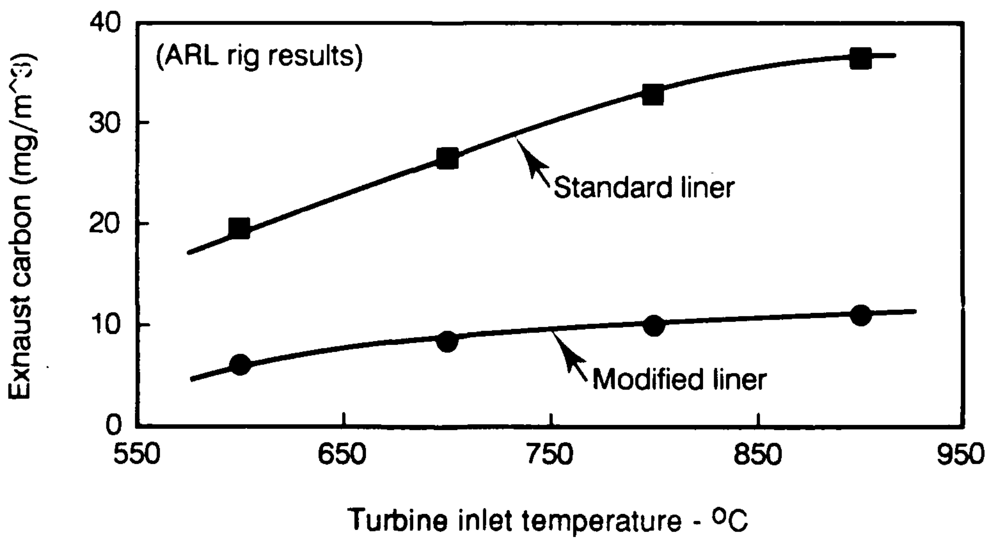



FIG. 14 EXHAUST CARBON VS TURBINE INLET TEMPERATURE

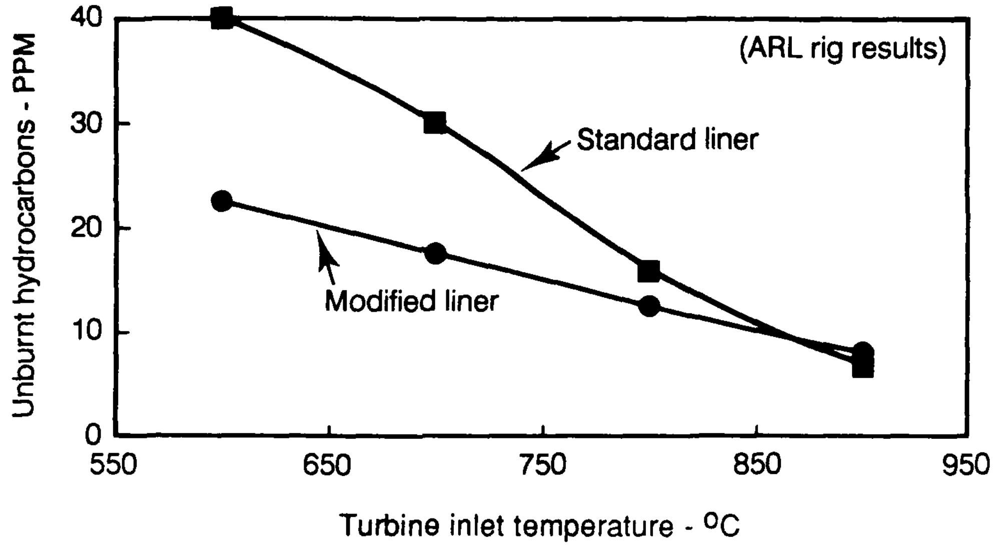



FIG. 15 UNBURNT HYDROCARBONS VS TURBINE INLET TEMPERATURE

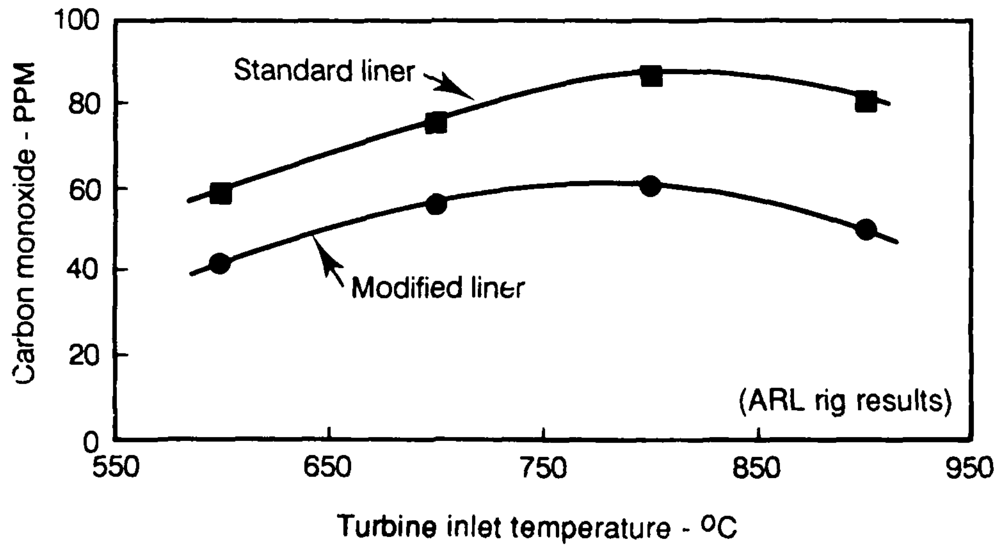



FIG. 16 CARBON MONOXIDE VS TURBINE INLET TEMPERATURE

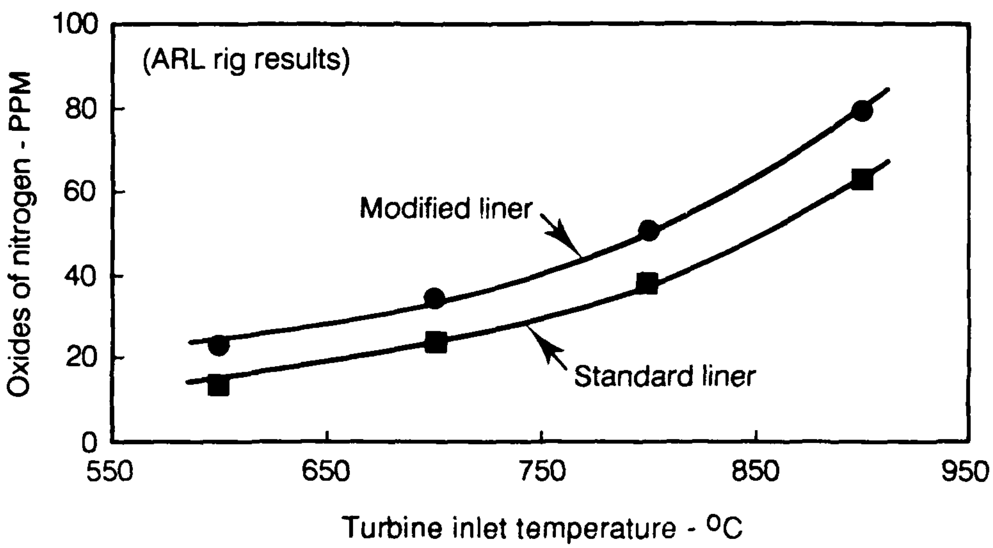



FIG. 17 OXIDES OF NITROGEN VS TURBINE INLET TEMPERATURE

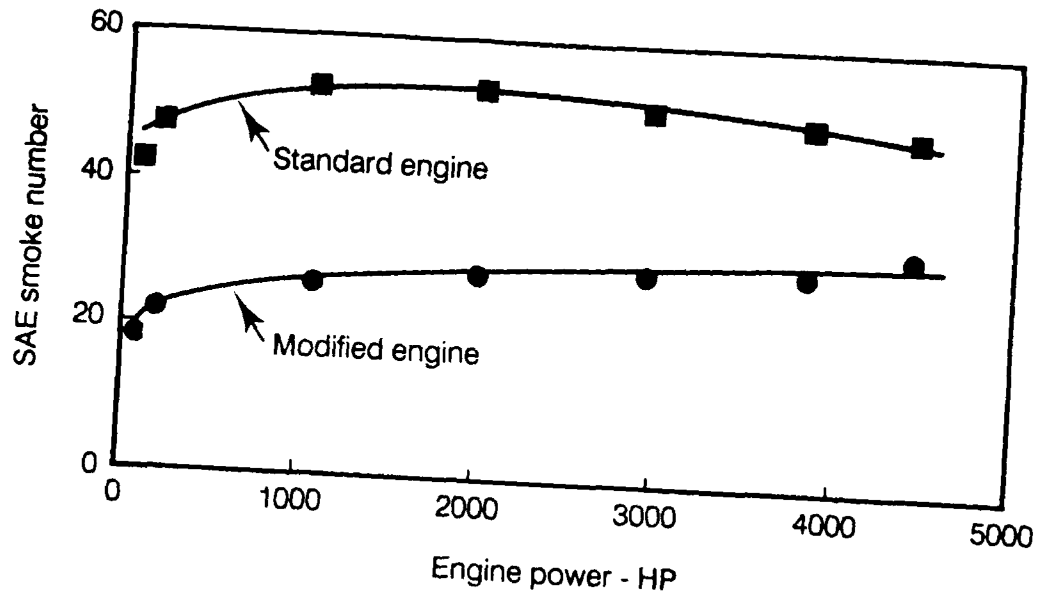



FIG. 18 SAE SMOKE NUMBER VS ENGINE POWER

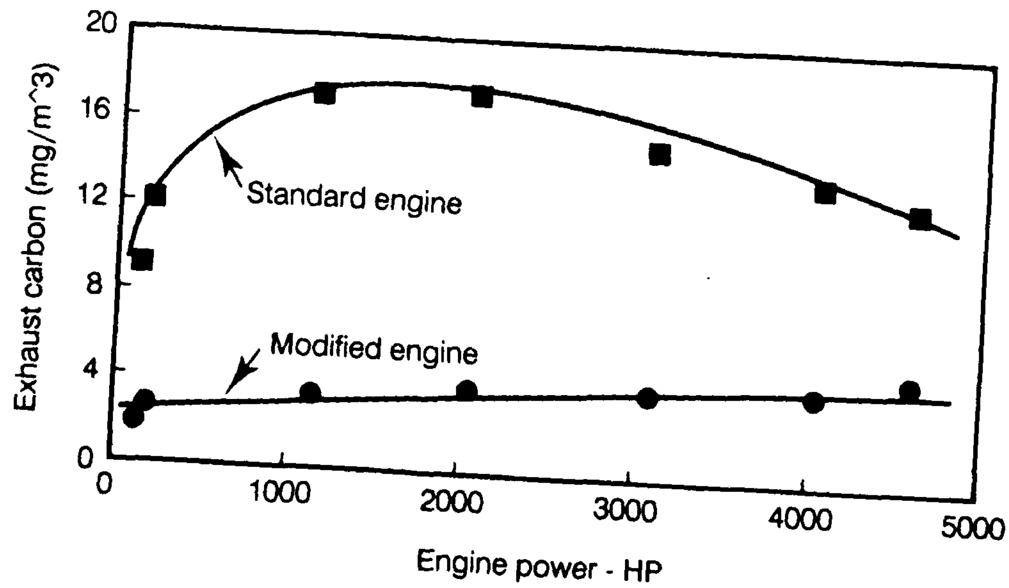



FIG. 19 EXHAUST CARBON VS ENGINE POWER

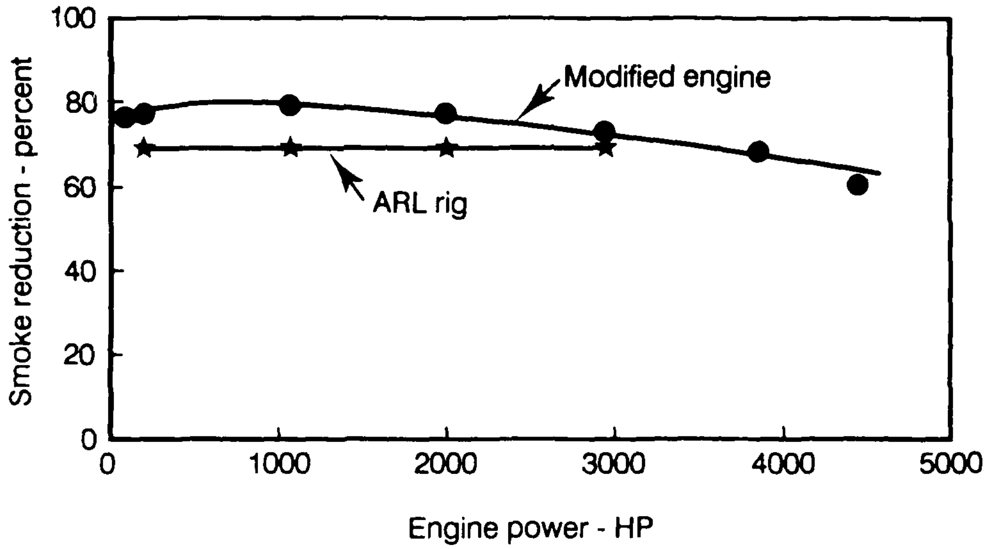



FIG. 20 SMOKE REDUCTION VS ENGINE POWER(ENGINE AND ARL RIG)

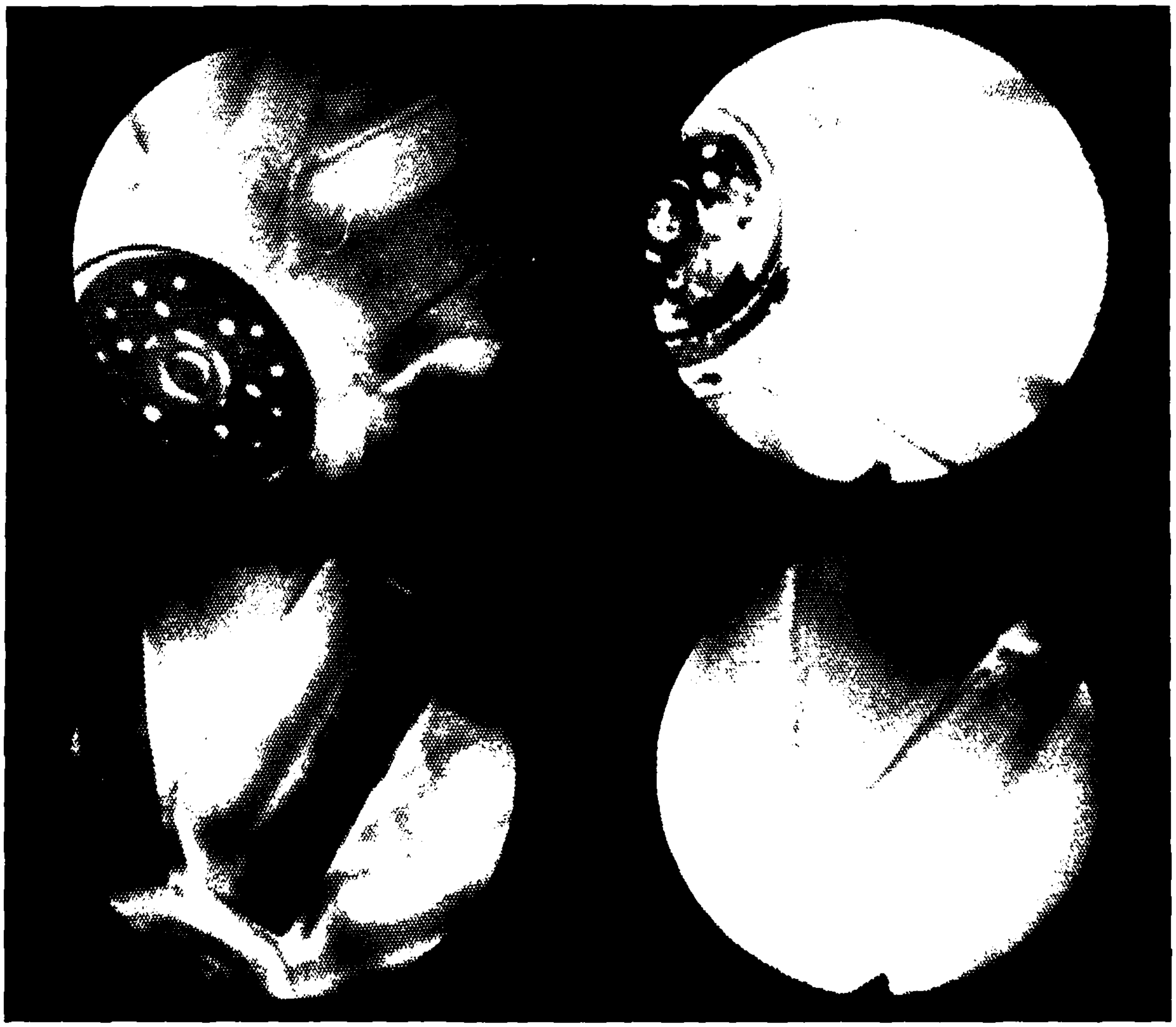


FIG. 21 BOROSCOPE PHOTOGRAPHS OF CARBON BUILD UP IN STANDARD (LEFT) AND MODIFIED LINER (RIGHT)

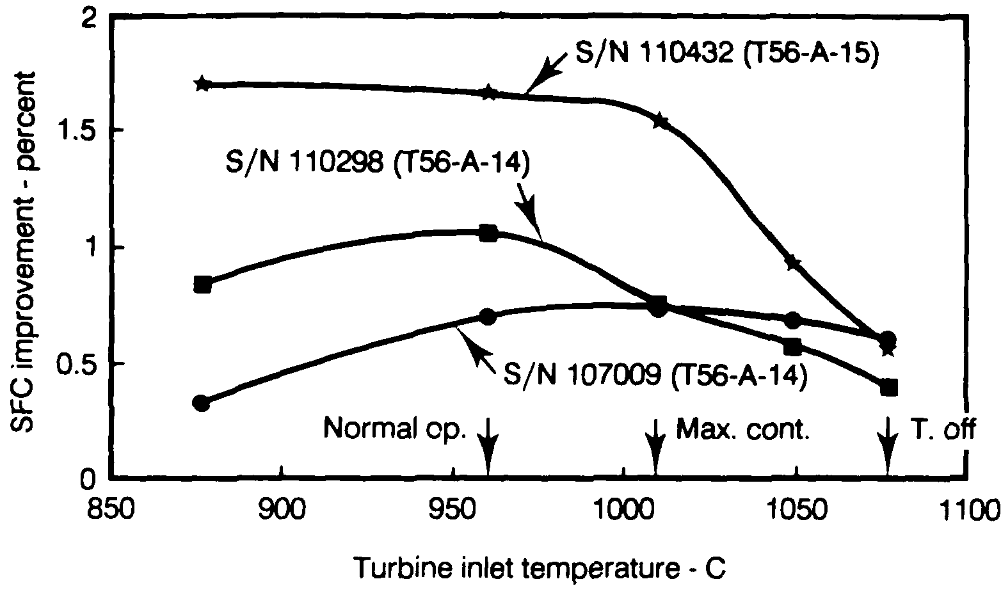



FIG. 22 SPECIFIC FUEL COMSUMPTION IMPROVEMENT

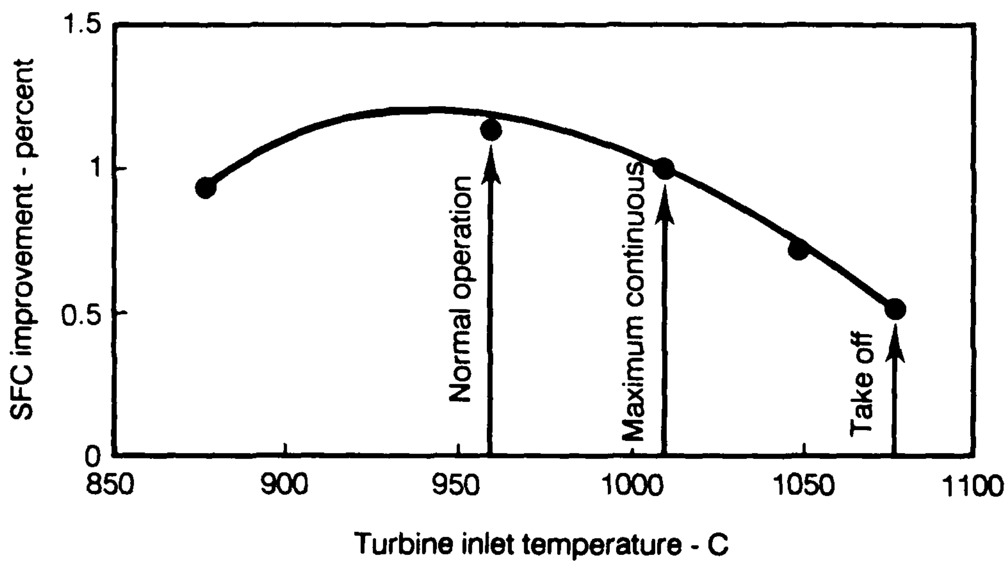



FIG. 23 SPECIFIC FUEL CONSUMPTION IMPOVEMENT (AVERAGE OF THREE ENGINES)

FIG. 24 P-3C ORION AIRCRAFT A9-661 WITH MODIFIED ENGINE FITTED TO NUMBER 3 POSITION

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16. ABSTRACT

Aeronautical Research Laboratory (ARL) has been working to reduce smoke emissions from the Allison T56 engines used in the Lockheed P-3C Orion aircraft operated by the Royal Australian Air Force (RAAF). The work consisted of a literature survey, design and manufacture of a water tunnel model, water tunnel testing of various modifications to improve the fluid dynamics of the combustion system, testing the modifications in a single liner combustion test rig, smoke emission comparative tests in ground run engine trials, performance tests in a calibrated test cell and flight trials of a modified engine. The modification that was developed in this program was found to significantly reduce smoke emissions and give substantial improvements in the specific fuel consumption of the engine. In addition, there were indications, in line with theoretical predictions, that the modification would extend the life of the hot end components of the engine.

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16. ABSTRACT (CONT).

This report describes the work up to August 1989 and outlines the final program on burner outlet surveys that will complete the program.

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